

Luminosity Functions of Elliptical Galaxies at $z < 1.2$

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ABSTRACT

The luminosity functions of E/S0 galaxies are constructed in 3 different redshift bins ($0.2 < z < 0.55$, $0.55 < z < 0.8$, $0.8 < z < 1.2$), using the data from the Hubble Space Telescope Medium Deep Survey (HST MDS) and other HST surveys. These independent luminosity functions show the brightening in the luminosity of E/S0s by about $0.5 \sim 1$ magnitude at $z \sim 1$, and no sign of significant number evolution. This is the first direct measurement of the luminosity evolution of E/S0 galaxies, and our results support the hypothesis of a high redshift of formation ($z > 1$) for elliptical galaxies, together with weak evolution of the major merger rate at $z < 1$.

Subject headings: cosmology: observations - galaxies: evolution - galaxies:elliptical and lenticular, cD - galaxies: luminosity function, mass function

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1. Introduction

The images of faint galaxies taken with the Wide Field and Planetary Camera (WFPC2) on the Hubble Space Telescope (HST) have provided invaluable information on the morphology of galaxies when the universe was about half its present age. With these data, reliable morphological classification is possible down to a magnitude limit of $I < 22 \sim 23$, and we have identified the morphological nature of the galaxies which dominate the number counts at faint magnitudes (Im et al. 1995a, 1995b; Griffiths et al. 1994; Casertano et al. 1995; Driver, Windhorst, & Griffiths 1995; Glazebrook et al. 1995; Abraham et al. 1996). For E/S0 galaxies, Im et al. (1995c) find evidence for mild luminosity evolution and no strong merging activity at $z < 1$, using the observed size and colour distributions. Likewise, the HST observations of E/S0 galaxies in clusters at moderate and high redshifts show little sign of strong luminosity evolution (Dickinson 1995).

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Lilly et al. (1995a) and Ellis et al. (1995) have shown luminosity functions of the total or colour-divided galaxy population at different redshifts and tried to constrain the evolution of faint galaxies up to $z \sim 1$. In particular, Lilly et al. (1995a) divided the galaxies into two subsamples according to their colors (red or blue), and then showed that the luminosity of red galaxies evolves mildly, in contrast with the blue galaxies. This result on the red galaxies is consistent with the HST observations of ellipticals, but because of the lack of morphological classification for most of the galaxies in the Lilly et al. sample, detailed constraints on the luminosity evolution of E/S0 galaxies have not been obtained in their study. The HST data can provide such morphological information, and we will thus construct luminosity functions of *E/S0 galaxies* at moderate to high redshifts in order to study their evolution.

2. Data

Our selection of elliptical galaxies comes from the full HST MDS which observes random fields using WFPC2, and we have also included generically similar archival data from a strip of sky originally surveyed in primary mode by Groth et al. (1994). All of these fields were observed in both the V and I bands (F606W and F814W). The detection limit for each field covers the range $I \simeq 23 \sim 25$ and $V \simeq 24 \sim 25.5$. For each object detected, the observed image is fitted with simple model profiles (point source, $r^{1/4}$ profile and exponential profile) using a 2-dimensional maximum likelihood technique (Ratnatunga et al 1995). We identify E/S0 galaxies via (i) morphology and (ii) luminosity profile. Point (ii) is an important step which is needed in order to exclude dwarf elliptical galaxies (dE) from our sample. The dE galaxies have different photometric properties from normal ellipticals (e.g, see Im et al. 1995b and references therein). From 56 HST WFPC2 fields, we find 376 elliptical galaxies at $18 < I < 22$, the same sample as that used in the previous study of number counts and constraints on cosmological parameters using these galaxies (Im et al. 1995c). For a dozen ellipticals in our sample, spectroscopic observations were obtained with the KPNO 4 meter using the Cryogenic Camera and RC Spectrograph with multi-slit masks during observing runs in October 1994 and April 1995. Sufficiently high signal-to-noise spectra were obtained during 2 to 3 hour exposures in order to measure redshifts. Redshifts were generally determined through identification of the CaII H&K absorption feature in each spectrum, at a rest wavelength of $\sim 4000\text{\AA}$. Redshifts for 11 E/S0s in the archived HST data from the Groth-Westphal field at 14H+52° were taken from Lilly et al.(1995b). These latter redshifts were extremely useful since they covered the range from $z \sim 0.6$ to $z \sim 1.2$.

3. Estimate of Photometric Redshifts

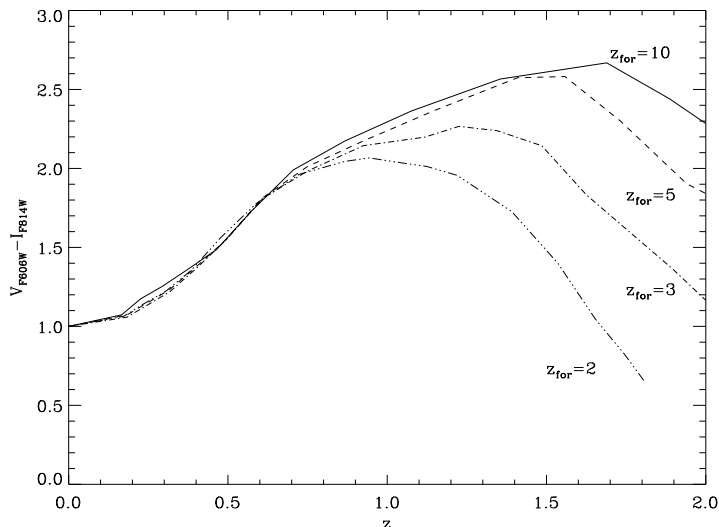


Fig. 1: The predicted $V - I$ colors of E/S0 galaxies vs. redshift. Note that the $z - (V - I)$ relation at $z < 1$ is nearly independent of the formation redshift z_{for} .

Previous studies have shown that the spectral energy distribution of present-day normal E/S0 galaxies can be well fitted by a single starburst model with an age of more than 10 Gyr (Bruzual & Charlot 1993; Arimoto & Yoshii 1986; Guiderdoni & Rocca-Volmerange 1987). According to these models, the color of E/S0 galaxies is quite insensitive to luminosity evolution up to $z \sim 1$ (Fig. 1). We therefore use the $V - I$ color of E/S0 galaxies to estimate redshifts. The use of the HST V and I bands is advantageous in this respect since they are relatively insensitive to the detailed shape of individual spectra, owing to their broad widths. We also use the half light radii of the E/S0s in order to complement the photometric estimation of redshifts. For a given apparent magnitude, galaxies with lower surface brightness (or larger angular sizes) are likely to be at higher redshifts than galaxies with higher surface brightness (or smaller angular sizes) because of the $(1 + z)^4$ surface brightness dimming effect (Im et al. 1995a).

In Fig.2, we show estimated photometric redshifts vs. spectroscopic redshifts for a subsample of E/S0 galaxies. The photometric redshifts estimated using colors and sizes are accurate to within an error of about 0.08 at low redshifts and about 0.13 at high redshifts.

In order to calculate absolute magnitudes, the K-correction has been applied, but no evolutionary correction was used since our intention is to measure the degree of evolution of the luminosity function. The error in z_{phot} leads to an uncertainty of about 0.5 mag in the absolute magnitudes at $0.2 < z < 1.2$.

4. Luminosity function of elliptical galaxies at $z < 1.2$

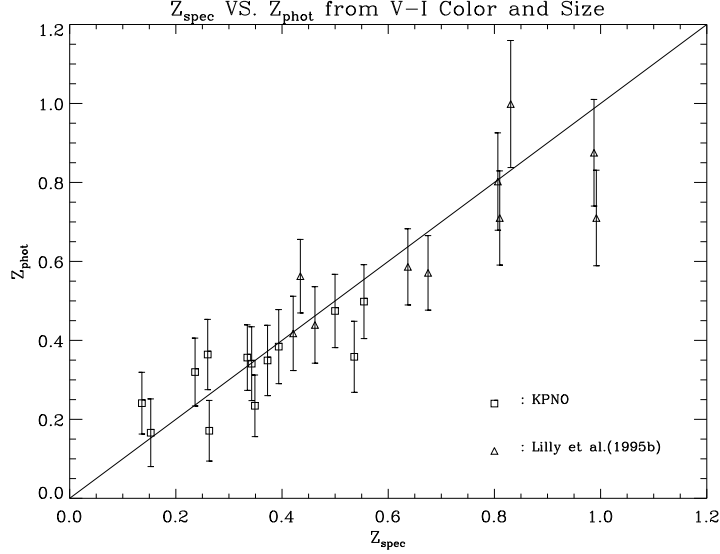


Fig. 2: The measured spectroscopic redshifts (z_{spec}) vs. (z_{phot}), redshifts estimated photometrically using the $V - I$ colors, the apparent magnitude and the half light radii of E/S0 galaxies. The accuracy of z_{phot} is about $\delta z_{\text{phot}} < 0.1$ at $z < 0.5$ and $\delta z_{\text{phot}} \sim 0.13$ at $z \sim 1$.

We have constructed the luminosity function of E/S0 galaxies using the V/V_{max} technique (Huchra & Sargent 1973; Lilly et al. 1995a) within three redshift bins, i) $0.2 < z < 0.55$, ii) $0.55 < 0.8$, and iii) $0.8 < z < 1.2$ under the assumption of two different sets of cosmological parameters: A) $\Omega_{\text{matter}}(\text{hereafter}, \Omega_m) = 1$, $\Lambda = 0$, and B) $\Omega_m = 0.2$, $\Lambda = 0.8$. Each redshift bin contains about 120 galaxies, and this gives about 20 ~ 30 galaxies available within each absolute magnitude bin for the determination of the luminosity functions (LFs). The calculated LFs are plotted in Fig.3. and Fig.4., along with the E/S0 LF from the CfA redshift survey (Marzke et al. 1995). The error on each point is obtained by a bootstrap algorithm. There is a clear trend that the LF moves towards brighter magnitudes with increasing redshift, i.e. we observe luminosity evolution. Taking into account the uncertainty of about 0.5 in the estimate of absolute magnitudes, there thus appears to be luminosity evolution by 0.5 ± 0.5 in I magnitude from $z \sim 0.4$ to $z \sim 0.7$, and 1 ± 0.5 magnitude brightening from $z \sim 0.4$ to $z \sim 1$. The corresponding expected luminosity evolution at $z \sim 1$ from spectral evolution models is about 0.7 to 1.4 ($z_{\text{for}} > 3$), consistent with our findings (Bruzual & Charlot 1993; Colin et al 1993; Im et al. 1995c; Roche et al. 1995). It is not clear whether there is luminosity evolution from $z=0$ to $z=0.4$, because of the uncertainty in the value of M_* for the local elliptical LF (Marzke et al. 1995; Loveday et al. 1992; Zucca et al. 1994) as well as the 0.5 magnitude uncertainty in our LF, but the models predict about 0.3 magnitude of brightening at this redshift. There is observational evidence for the existence of intermediate age stellar populations in cluster E/S0s, implying that there were secondary bursts of star formation (e.g., Couch & Sharples 1987). Starbursting E/S0s may look more irregular and bluer than the normal ellipticals, which are not found in our sample. Hence, our result does not necessarily exclude such models of E/S0s with the secondary starbursts (Charlot & Silk 1994).

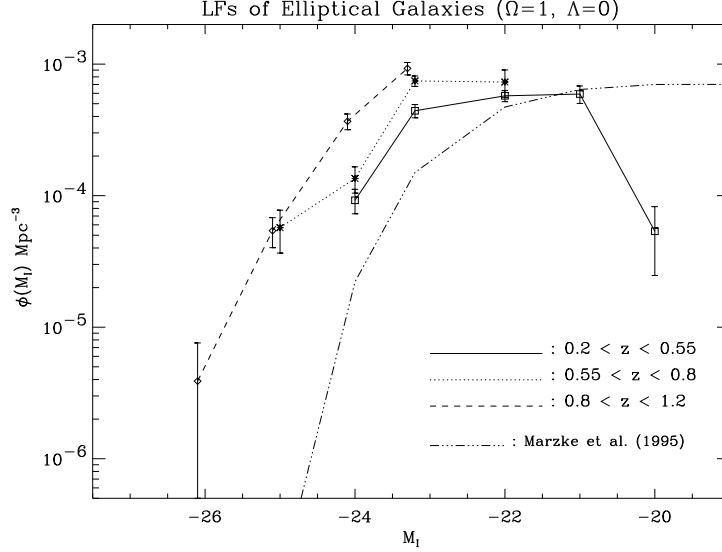


Fig. 3: The luminosity function of E/S0 galaxies at i) $0.2 < z < 0.55$ (solid line), ii) $0.55 < z < 0.8$ (dotted line), and iii) $0.8 < z < 1.2$ (dashed line). Cosmological parameters $\Omega_m = 1$ and $H_0 = 50 \text{ km sec}^{-1} \text{ Mpc}^{-1}$ are used to derive the luminosity functions. The luminosity function of E/S0 at $z \sim 0$ from Marzke et al. (1995) is also plotted assuming $Z - I = 2.4$.

To show the completeness of our sample, we list V/V_{max} values and the number of ellipticals used in Table 1. When $V/V_{max} = 0.5$, the sample can be considered complete and there is then no strong bias in the estimate of the LF (Huchra & Sargent 1973; Zucca et al. 1994). In Table 1, we find that $V/V_{max} \simeq 0.5$ for most cases except for a few outliers, and we conclude that our result is not affected by any bias due to the incompleteness of the sample. Also, we find that the V/V_{max} is distributed uniformly from 0 to 1 (not shown in this paper). The elliptical galaxies live preferentially in clusters and the derived LF could be biased by ellipticals in a few large clusters. If this is the case, the V/V_{max} would be clumped around the certain value where the cluster lies. We do not find this kind of trend, thus our result is not affected by large clusters.

In order to provide a more quantitative result, we have also estimated parameters for the LFs using the STY method (Sandage, Tamman, & Yahil 1979; Loveday et al. 1992; Marzke et al. 1995), on the assumption that they are described by the Schechter form (Schechter 1976). Because of the lack of a sufficient number of galaxies to fit the LF over a reasonable magnitude range, the estimated parameters (α and M_*) are rather unstable, and the apparent steepening of the estimated slope at high redshift should not be considered seriously (first and second rows of Table 2). In order to obtain a more stable fit, we therefore used a fixed $\alpha = -0.85$ (Marzke et al. 1995) and estimated the change in M_* . The third row of Table 1 shows M_* estimates by this method, and we clearly see the brightening of M_* with redshift. We also note that the observed I magnitude is roughly equivalent to the rest frame B-magnitude at $z \sim 1$ within a few tenths of magnitude (Lilly et al. 1995a). For this reason, we constructed the luminosity function at $z \sim 1$ without applying K-correction, and estimated the M_{B*} using $\alpha = -0.85$. This way, we get

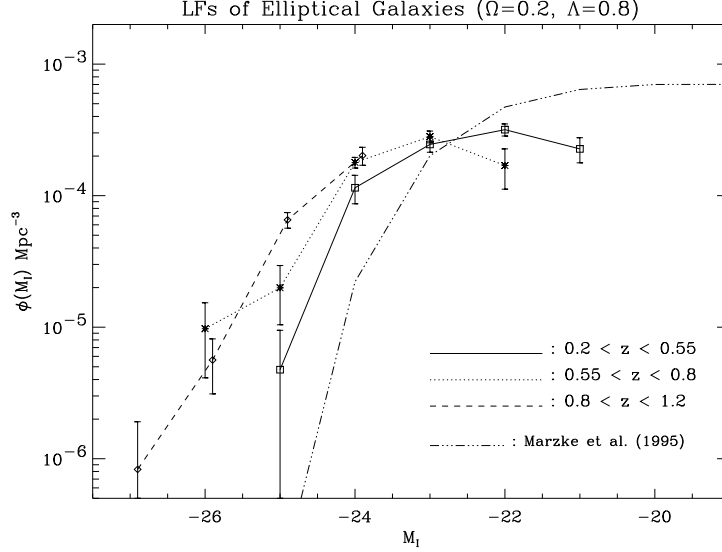


Fig. 4: The luminosity function of E/S0 galaxies at i) $0.2 < z < 0.55$ (solid line), ii) $0.55 < z < 0.8$ (dotted line), and iii) $0.8 < z < 1.2$ (dashed line), on the assumption of $\Omega_m = 0.2$, $\Lambda = 0.8$ and $H_0 = 50 \text{ km sec}^{-1} \text{ Mpc}^{-1}$. The luminosity function of E/S0 at $z \sim 0$ from Marzke et al. (1995) is also plotted assuming $Z - I = 2.4$.

$M_{B*} = -20.4 \sim -21.1 + 5 \log(h)$ (note that $M_{B*} \simeq -19.5 + 5 \log(h)$ at $z=0$: Efsthathiou et al. 1988; Marzke et al. 1995) consistent with our finding of the luminosity evolution in I magnitude (fifth row of the Table 2).

If, as a result of mergers, the average mass of ellipticals is a decreasing function of look-back time, our result is also consistent with strong luminosity evolution ($>> 1 \text{ mag}$) at $z=1$. However, this is unlikely since the strong merging activity accompanies the remarkable decrease of the number density as a function of redshift, which is not observed in our data (however, see discussions below for a possible loophole in this argument).

In order to quantify the possible number evolution of E/S0s, we tried to estimate ϕ_* using the parameters in the third row of Table 2 and the observed LFs in Fig. 3. The observed LFs show ϕ_* may have decreased by about 50 % since $z=1$ if $\Omega_m = 1$ and $\Lambda = 0$. If $\Omega_m = 0.2$ and $\Lambda = 0.8$, the ϕ_* value hardly changes as a function of redshift, probably by less than 30 % (see the fourth row of Table 2). If the value of ϕ_* is indicative of the number density evolution (i.e., M_* is fixed: see Im et al. 1995c), we expect that about 4 – 20 % of the present day galaxies are produced via major merging since $z = 1$, adopting the present day merger rate to be $0.005 \sim 0.023 \text{ Gyr}^{-1}$ (Carlberg 1995) and the look-back time of $\sim 9 \text{ Gyr}$. Today, roughly 20 – 25 % of galaxies in the volume limited sample are E/S0s (Buta et al. 1994; Lauberts & Valentijn 1989), thus we expect the number evolution of more than 16 – 100 % to be observed if the ellipticals are the products of major merging. Similarly, we get the upper limit of the “major merger rate” (defined here the fraction of interacting pairs per unit time) to be roughly $\lesssim 0.01 \text{ Gyr}^{-1}$ using our lower limit of $\phi_*(z=1) > 0.7 \phi_*(z=0)$. If the merger rate evolved as strongly as $\sim (1+z)^4$, the number density

of ellipticals at $z=1$ would be much less than 70 % of the present day value. Hence models with the strong major merger rate evolution seem to be excluded (e.g., Carlberg 1992).

However, the strong merger rate evolution with strong luminosity evolution could be reconciled with our data if the value of Ω is locally low. The local low density universe has been suggested to explain the high value of H_0 with $\Omega_m = 1$ (e.g., Wu et al. 1995). In order to reconcile the latest estimates of H_0 with the $\Omega_m = 1$ universe, one can assume that our local universe ($z < 0.2$) has a mass density only 10 \sim 20 % of the total mass density of the universe. Thus, at sufficiently high redshift ($z > 0.5$), the mass density needs to be about 5 to 10 times higher than that in our local universe, and the same for the number density of galaxies if the ratio of dark to luminous matter is roughly constant. Our result appears to show the number density of E/S0s increases as a function of look-back time $z=0$ when $\Omega_m = 1$, but not as much as the factor of 5–10. The local low density universe appears to be excluded, but the apparent deficit of E/S0s at $z \sim 1$ could simply be due to the strong number evolution caused by the strong major merger rate evolution. In that case, the local low density universe *with* the strong merger rate evolution may be consistent with our data (But for observational evidences against the strong major merger rate evolution, see Neuschaefer et al. 1995, 1996; Woods et al. 1995).

5. Conclusions

We have constructed the luminosity functions of elliptical galaxies using data from HST MDS and archived HST surveys. Redshifts of these E/S0s have been determined using $V - I$ colors and sizes to an accuracy of ~ 0.1 up to $z \sim 1$. From the constructed luminosity functions, we find luminosity evolution of about 1 ± 0.5 mags at $z \sim 1$. On the other hand, we exclude strong number evolution of elliptical galaxies, and our data are consistent with a merger rate of $\lesssim 0.01 \text{ Gyr}^{-1}$ with very weak major merger rate unless the mass density of the universe is locally low. This latter result supports our earlier findings (Im et al. 1995c) on the basis of the size and colour distributions of E/S0s.

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TABLE 1
 $V/V_{max}(\text{NUMBER})$

Absolute Magnitude	$\Omega = 1, \Lambda = 0$			$\Omega = 0.2, \Lambda = 0.8$		
	$0.2 < z < 0.55$	$0.55 < z < 0.8$	$0.8 < z < 1.2$	$0.2 < z < 0.55$	$0.55 < z < 0.8$	$0.8 < z < 1.2$
$-27.5 \sim -26.5$	...	...	...	...	...	0.74(1)
$-26.5 \sim -25.5$	...	...	0.76(1)	...	0.66(3)	0.76(5)
$-25.5 \sim -24.5$	...	0.56(7)	0.61(12)	0.58(1)	0.54(7)	0.52(33)
$-24.5 \sim -23.5$	0.38(8)	0.50(17)	0.52(41)	0.39(20)	0.51(62)	0.54(35)
$-23.5 \sim -22.5$	0.57(43)	0.50(90)	0.53(20)	0.55(49)	0.51(68)	...
$-22.5 \sim -21.5$	0.56(53)	0.54(33)	...	0.57(59)	0.37(7)	...
$-21.5 \sim -20.5$	0.65(44)	...	...	0.68(21)	...	...
$-20.5 \sim -19.5$	0.95(2)	...	...	...	...	...

TABLE 2
PARAMETERS OF LFs

	$\Omega = 1, \Lambda = 0$			$\Omega = 0.2, \Lambda = 0.8$		
	$0.2 < z < 0.55$	$0.55 < z < 0.8$	$0.8 < z < 1.2$	$0.2 < z < 0.55$	$0.55 < z < 0.8$	$0.8 < z < 1.2$
α	-0.25 ± 0.19	-0.66 ± 0.29	-1.50 ± 0.65	-0.26 ± 0.19	-0.72 ± 0.26	-1.67 ± 0.50
M_*	-22.3 ± 0.2	-23.1 ± 0.3	-23.7 ± 0.5	-22.7 ± 0.2	-23.7 ± 0.3	-24.5 ± 0.5
M_*	-22.3 ± 0.1	-22.8 ± 0.1	-23.0 ± 0.1	-22.7 ± 0.1	-23.4 ± 0.1	-23.7 ± 0.1
ϕ_*	$(1.2 \pm 0.3) \times 10^{-3}$	$(1.7 \pm 0.4) \times 10^{-3}$	$(2.1 \pm 0.7) \times 10^{-3}$	$(5.9 \pm 0.2) \times 10^{-4}$	$(5.9 \pm 0.2) \times 10^{-4}$	$(5.8 \pm 0.3) \times 10^{-4}$
M_{B*}	-21.9 ± 0.1	-22.6 ± 0.1

$H_0 = 50 \text{ km sec}^{-1} \text{ Mpc}^{-1}$ is used

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